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Solar Sailing Kinetic Energy Interceptor (KEI) Mission for Impacting/Deflecting Near-Earth Asteroids

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A solar sailing mission architecture, which requires at least ten 160-m, 300-kg solar sail spacecraft with a characteristic acceleration of 0.5 mm/s^2, is proposed as a realistic near-term option for mitigating the threat posed by near-Earth asteroids (NEAs). Its mission feasibility is demonstrated for a fictional asteroid mitigation problem created by AIAA. This problem assumes that a 200-m asteroid, designated 2004WR, was detected on July 4, 2004, and that the expected impact will occur on January 14, 2015. The solar sailing phase of the proposed mission for the AIAA asteroid mitigation problem is comprised of the initial cruise phase from 1 AU to 0.25 AU (1.5 years), the cranking orbit phase (3.5 years), and the retrograde orbit phase (1 year) prior to impacting the target asteroid at its perihelion (0.75 AU from the sun) on January 1, 2012. The proposed mission will require at least ten kinetic energy interceptor (KEI) solar sail spacecraft. Each KEI sailcraft consists of a 160-m, 150-kg solar sail and a 150-kg microsatellite impactor. The impactor is to be separated from a large solar sail prior to impacting the 200-m target asteroid at its perihelion. Each 150-kg microsatellite impactor, with a relative impact velocity of at least 70 km/s, will cause a conservatively estimated ΔV of 0.3 cm/s in the trajectory of the 200-m target asteroid, due largely to the impulsive effect of material ejected from the newly-formed crater. The deflection caused by a single impactor will increase the Earth-miss-distance by $0.45R_\oplus$ (where $R_\oplus$ denotes the Earth radius of 6,378 km). Therefore, at least ten KEI sailcraft will be required for consecutive impacts, but probably without causing fragmentation, to increase the total Earth-miss-distance by $4.5R_\oplus$. This miss-distance increase of 29,000 km is outside of a typical uncertainty/error of about 10,000 km in predicting the Earth-miss-distance. A conventional Delta II 2925 launch vehicle is capable of injecting at least two KEI sailcraft into an Earth escaping orbit. A 40-m solar sail is currently being developed by NASA and industries for a possible flight validation experiment within 10 years, and a 160-m solar sail is expected to be available within 20 years.

I. Introduction

The spectacular collision of comet Shoemaker-Levy 9 with Jupiter in July 1994 was a clear evidence of the fact that the risks of impacts upon Earth by near-Earth objects (NEOs) is very real. In response, the U.S. Congress funded a 10-year survey to locate and track 90% of the NEOs with diameters of 1 km or greater, the impacts of which could threaten the extinction of civilization. In the course of this ongoing search, hundreds of thousands of smaller asteroids have been discovered, many similar in size to the 60-m object that exploded above Tunguska, Siberia on June 30, 1908 with an energy level of 10 megatons of TNT, destroying essentially everything within a 25-km radius. Air-bursts with an energy level of 5 kilotons of TNT, such as that due to the 10-m object that disintegrated over Tagish Lake, AK in 2000, are estimated to occur on an annual basis.[1]

It is now widely accepted by scientists and geologists that an impact by a large asteroid of greater than 10 km in diameter caused the extinction of the dinosaurs. A 2-km object is known to be capable of causing catastrophic alteration of the global ecosystem which may lead to the end of civilization. Ocean impacts of even smaller objects are of some concern because the destructive potential caused by the resulting tsunamis may be above that from a same-size object's land impact. There is also a growing concern that such a

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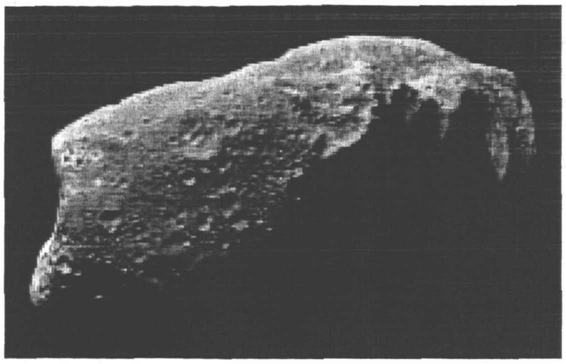


Figure 1. Asteroid 243 Ida, imaged by the Galileo spacecraft's solid-state imaging system at ranges of 3,057 to 3,821 km on August 28, 1993 (Courtesy of NASA). Galileo flew within 2,400 km of the 52-km Ida at a relative velocity of 12.4 km/s.

devastating impact in the wrong area at the wrong time could be mistaken as a nuclear attack, possibly leading to a nuclear war. The probability of a major impact to cause the extinction of humanity is extremely low, but it is not zero.

Unlike many other natural disasters, such as earthquakes, tsunamis, hurricanes, and tornadoes, which cannot be prevented, the threat posed by NEOs can be mitigated given adequate warning time. This paper presents a realistic near-term option for mitigating such catastrophic impacts of NEOs. In Section II, the problem of mitigating the threat posed by near-Earth asteroids and comets is briefly reviewed, and a viable solution to such a truly complex problem is introduced. Section II is intended to outline this technically challenging, asteroid mitigation problem and its realistic near-term engineering solution which utilizes the recent advances in solar sail technology. A mission design problem of AIAA for mitigating the threat of a fictional 200-m asteroid will be described in Section III, and then details of the proposed solar sailing kinetic impactor mission concept of intercepting, impacting, and deflecting near-Earth asteroids, as applied to the AIAA asteroid mitigation problem with a 10-year mission lead time, will be presented in Section IV.

II. Asteroid Mitigation Problem and Its Solar Sailing Solution

The impact of an object smaller than 50 m in diameter is often naturally mitigated by the Earth's atmosphere. As the typical small meteoroids enter the atmosphere, they often burn up or explode before they hit the ground. If they burn up, they are called meteors; if they explode, they are called bolides.

A near-Earth asteroid (NEA) refers to any asteroid with a perihelion of less than 1.3 AU. If comets are included, then we speak of near-Earth objects (NEOs). If a NEA's perihelion is less than that of Earth, and its aphelion is greater than that of Earth, it is referred to as an Earth-crossing asteroid (ECA). All asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 AU or less and an absolute magnitude of 22.0 or less are considered Potentially Hazardous Asteroids (PHAs). Asteroids that cannot get any closer to the Earth than 0.05 AU ($\approx 117R_{\oplus}$) or are smaller than about 150 m in diameter are not considered PHAs. There are currently 672 known PHAs. A comet sometimes experiences net thrust caused by evaporating ices; this thrust varies significantly as a function of radial distance from the Sun, the comet's rotational axis and period, and the distribution of ices within the comet's structure. The precise trajectories of comets are thus less predictable, and an accurate intercept correspondingly more complex. Fortunately, the threat posed by comets appears to be small compared to the risks of impacts by NEAs, and thus this paper focuses on mitigating the threat posed mostly by NEAs. However, a further study should continue to address the difficult task of detecting and mitigating comets.

Early detection, accurate tracking, reliable precision orbit calculation, and characterization of physical properties of NEAs are prerequisites to any mitigation mission of deflecting NEAs. The early discovery of NEAs prior to impact using current ground-based optical sensors is not assured, and detection/tracking of small (1 km or less) NEAs is a difficult task given their low albedo and small size. Various concepts and approaches for advanced ground-based as well as space-based detection systems are being developed to allow

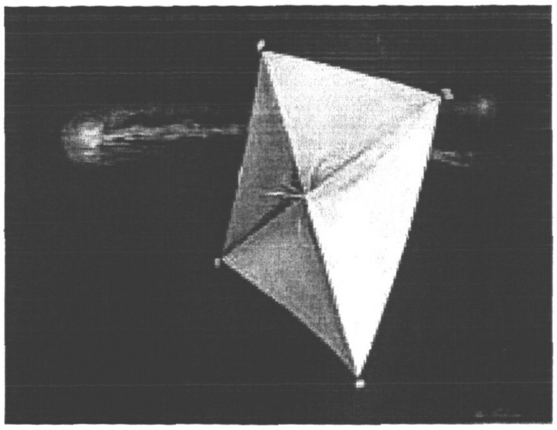


Figure 2. A large, 800-m solar sail proposed by JPL in 1977 for a rendezvous mission with Halley's comet for the 1986 passage.[18] Although it became an ill-fated mission concept of 1970s, it utilized the propellantless solar sailing concept for achieving a large orbital inclination change (> 90 deg) to reverse the orbital flight direction.

for adequate warning time.[2,3] Assuming that NEAs on a collision course can be detected prior to impact with a mission lead time of at least 10 years, however, the challenge becomes eliminating their threat, either by fragmenting/destroying the asteroid, or by altering its trajectory so that it will miss Earth. A variety of schemes, including a nuclear standoff detonation, mass drivers, kinetic-energy projectiles, laser beaming, and low-thrust deflection via electric propulsion or solar sails, have been already extensively investigated in the past for such a technically challenging, asteroid mitigation problem.[3–7] The feasibility of each approach to deflect an incoming hazardous object depends on its size, spin rate, composition, and the mission lead time. Until recently, it was assumed that destruction with thermonuclear weapons would be the most straightforward option in the short term. But the NEAR Shoemaker study of asteroid Mathilde,[2] as well as other studies of asteroids, suggest that many asteroids are essentially "rubble piles," rather than solid monolithic bodies such as a large asteroid shown in Fig. 1. Experiments show that a thermonuclear detonation within or near such a body of rubble piles would not effectively disperse the (now radioactive) constituent fragments,[8] which would continue following the same trajectory toward Earth.

Another option would be an impulsive change to the trajectory of the NEA, accomplished either in a single event, or gradually over an extended period. Applied correctly without causing fragmentation of a large asteroid into smaller pieces, the effect of such a ΔV would magnify over decades (or even centuries), eliminating the risk of collision with Earth. A gradual impulsive change might be accomplished by taking advantage of the Yarkovsky effect, in which a rotating asteroid experiences a minute non-radial thrust due to the absorption of sunlight and subsequent re-emission of heat. By varying the reflective and thermal characteristics of one area of an asteroid's surface, thrust could be created in the desired direction. Unfortunately, the requisite technologies for such an operation will not be readily available in the near future. Many of the previously proposed mitigation schemes utilizing such a low-thrust push/pull idea appear to be impractical. These include: Attaching large solar sails, mass drivers, or high-efficiency electric propulsion systems to a tumbling or spinning asteroid, painting an asteroid to change its albedo to utilize the Yarkovsky effect, and laser beaming to ablate small amounts of material from the surface of a tumbling asteroid. Some of these schemes may also require an extremely large number of a heavy launch vehicle.

A technology does currently exist for a sudden impulsive change, caused by the targeted kinetic impact of a spacecraft on the asteroid's surface. Again, the immediate effect would be small; but if applied long enough prior to a projected Earth impact, the deflection could be sufficient to cause a miss.[9–14] To be most effective, the impacting spacecraft would either have to be massive, or be moving very fast relative to the asteroid. Since current launch technology limits the mass (including propellant) that can be lifted into an interplanetary trajectory, we are therefore led to consider designs that would maximize impact velocity, and which would not require large amounts of fuel.

Propellantless solar sail propulsion, therefore, emerges as a realistic near-term option to such a technically challenging problem of mitigating the threat of NEAs. A previously proposed concept of using solar sails to tow or tug an asteroid requires an unrealistically large, 5 km $\times$ 5 km solar sail, which is not technically feasible to assemble in space. Furthermore, attaching such an extremely large solar sail to a tumbling asteroid will not be a simple task. However, solar sails have the potential to provide cost effective, propellantless propulsion that enables longer mission lifetimes, increased payload mass fraction, and access to previously inaccessible orbits (e.g., high solar latitude, retrograde heliocentric, and non-Keplerian). In the past, various solar sailing rendezvous missions with a comet or an asteroid have been studied.[15–19]

As illustrated in Fig. 2, a solar sailing concept was studied by JPL in 1977 for a rendezvous mission with Halley's comet for the 1986 passage.[18] Although it became an ill-fated mission concept of 1970s, that required a very large, 800-m solar sail to be deployed in space, it utilized the propellantless propulsion capability of solar sails to achieve a 145-deg orbital inclination change at 0.25 AU in order to rendezvous with Halley's comet in a retrograde orbit. The recent advances in lightweight deployable booms, ultra-lightweight sail films, and small satellite technologies are spurring a renewed interest in solar sailing and the missions it enables. Consequently, various near-term solar sailing missions and the associated technologies are being developed.[20–27] A 160-m solar sail required for the proposed asteroid mitigation mission is not currently available. However, a 40-m solar sail is being developed by NASA and industries for a possible flight validation experiment within 10 years, and a 160-m solar sail is thus expected to be available within 20 years.

The solar sailing mission described in this paper utilizes a solar sail to deliver a kinetic-energy impactor into a heliocentric retrograde orbit, which will result in a head-on collision with a target asteroid at its perihelion, thus increasing its impact velocity to at least 70 km/s. The feasibility of such a solar sailing concept, as applied to the asteroid mitigation problem, was recently presented in Ref. 28. A solar sailing mission architecture, which employs 160-m, 300-kg solar sail spacecraft with a characteristic acceleration of 0.5 mm/s^2, will be presented in Section IV as a realistic near-term option for mitigating the threat posed by NEAs. Its mission feasibility will be demonstrated for a fictional asteroid mitigation problem of AIAA to be described in the next section.

III. Collision of Asteroid 2004WR with Earth

A. AIAA's Asteroid Mitigation Problem

A fictional asteroid mitigation problem was created by AIAA for the 2004/2005 AIAA Foundation Undergraduate Team Space Design Competition (http://www.aiaa.org/content.cfm?pageid=221). A similar fictional asteroid mitigation problem, called the Defined Threat (DEFT) scenarios, has been created also for the 2004 Planetary Defense Conference. One of the four DEFT scenarios is about mitigating a fictional 200-m Athos asteroid with the predicted impact date of February 29, 2016.

The fictional asteroid mitigation problem of AIAA is briefly described as follows. On July 4, 2004, NASA/JPL's Near Earth Asteroid Tracking (NEAT) camera at the Maui Space Surveillance Site discovered a 0.205-km diameter Apollo asteroid designated 2004WR. This asteroid has been assigned a Torino Impact Scale rating of 9.0 on the basis of subsequent observations that indicate there is a 95% probability that 2004WR will impact the Earth. The expected impact will occur in the Southern Hemisphere on January 14, 2015 causing catastrophic damage throughout the Pacific region. The mission is to design a space system that can rendezvous with 2004WR in a timely manner, inspect it, and remove the hazard to Earth by changing its orbit and/or destroying it. The classical orbital elements of 2004WR are given in the J2000 heliocentric ecliptic reference frame as follows:

$$\begin{aligned}
\text{Epoch} &= 53200 \text{ TDB (July 14, 2004)} \\
a &= 2.15374076 \text{ AU} \\
e &= 0.649820926 \\
i &= 11.6660258 \text{ deg} \\
\omega &= 66.2021796 \text{ deg} \\
\Omega &= 114.4749665 \text{ deg} \\
M &= 229.8987151 \text{ deg}
\end{aligned}$$

The STK 5.0.4 software package, with a 9th-order Runge-Kutta integrator with variable stepsize and the planetary positions from JPL's DE405, was used by AIAA to create this set of orbital parameters of 2004WR.

It is further assumed that 2004WR is an S-class (stony-silicate) asteroid with a density of 2,720 kg/m^3 and that its estimated mass is 1.1×10^{10} kg. If 2004WR is an M-class (nickel-iron) asteroid, then its estimated mass would be 2.2×10^{10} kg.

B. N-Body Orbit Simulation of 2004WR

The initial position and velocity components in the heliocentric ecliptic coordinates are then obtained as

$$(X,\ Y,\ Z) = (3.17670340,\ \ 0.84877205,\ \ -0.66956611)\ \text{AU}$$
$$(\dot{X},\ \dot{Y},\ \dot{Z}) = (-0.0038834223,\ \ 0.0048780152,\ \ 0.00031250049)\ \text{AU/day}$$

where 1 AU = 149,597,870.691 km and 1 day = 24 hrs = 86,400 s.

Other orbital parameters of 2004WR in an ideal Keplerian orbit can be found as

$$r_p = 0.7542\ \text{AU (perihelion)}$$
$$r_a = 3.5533\ \text{AU (aphelion)}$$
$$v_p = 44\ \text{km/s (perihelion speed)}$$
$$v_a = 9.3\ \text{km/s (aphelion speed)}$$
$$P = 3.16\ \text{year (orbital period)}$$

An ideal Keplerian orbit simulation of 2004WR was performed first. The result indicated that its closest approach to Earth is about 0.035 AU, which is less than the MOID of 0.05 AU of a PHA. It also had a close encounter with Mars by 0.1 AU. After checking the ideal orbital characteristics of 2004WR, three different n-body software packages were used to confirm 2004WR's collision with Earth on January 14, 2015. These software packages were: JPL's Horizons,[29] CODES,[30] and SSCT,[31] all utilizing JPL's DE405 ephemeris data for the planetary positions. Orbit simulation results of using these packages indicate that 2004WR misses Earth by $1.6R_\oplus$ ($\approx 10,000$ km from the Earth center). This Earth-miss-distance prediction of approximately 10,000 km is in fact caused by the inherent uncertainty (not the numerical integration error) associated with the complex n-body orbital simulation problem. A detailed comparison of the computational models used by these software packages, including the STK used by AIAA, is beyond the scope of this paper, and it is left for a future study.

Although AIAA's asteroid problem statement claims that the expected impact of 2004WR will occur in the Southern Hemisphere on January 14, 2015, it is important to point out some inherent uncertainties associated with the practical orbit determination problem. In practice, ground-based optical observations of an asteroid during the first several days after its discovery are known to result in an orbit determination uncertainty of 70,000 km in position and 50 m/s in velocity. Further continuous optical tracking and observations, probably for over one year, may reduce the orbit determination uncertainty to 100 km and 5 cm/s. Additional radar observations can further reduce the orbit determination uncertainty to 10 km and 0.5 cm/s. A velocity uncertainty of 0.5 cm/s for an asteroid at epoch results in an Earth-miss-distance prediction uncertainty of 15,000 km after 10-year orbit propagation. Therefore, a future asteroid detection/tracking system will require the orbit determination accuracy better than 10 km and 0.5 cm/s to avoid serious false alarms, as well as to increase the mitigation mission reliability.

IV. Solar Sailing Kinetic Energy Interceptor (KEI) Mission

A. Kinetic-Impact ΔV Estimation

The simplest deflection approach is to impact the target NEA with a massive projectile at a high relative speed. However, a successful asteroid deflection mission will require accurate modeling and prediction of the change in velocity caused by the interceptor's impact. The effective impulse imparted to the asteroid will be the sum of the pure kinetic impulse (linear momentum) of the interceptor, plus the impulse due to the thrust of material being ejected from the impact crater. This last term can be very significant (even dominant), but its magnitude depends strongly upon the density and yield strength of the material of which the asteroid is composed, as well as the mass and relative velocity of the interceptor.

For example, a head-on impact (at a relative velocity of 70 km/sec) of a 150 kg impactor on a 200-m, S-class asteroid (with a density of 2,720 kg/m^3) results in a pure kinetic-impact ΔV of approximately 0.1

cm/s. If the asteroid is composed of hard rock, then the modeling of crater ejecta impulse from previous studies[4,5] would predict an additional ΔV of 0.2 cm/s, which is double the pure kinetic-impact ΔV. However, if the asteroid were composed of soft rock, the previous studies would instead predict an additional ΔV of 0.55 cm/s, which is more than five times the pure kinetic-impact ΔV. Thus, an accurate modeling and prediction of ejecta impulse for various asteroid compositions is a critical part of the most kinetic-impact approaches. Recent empirical research[32] would not only allow us to substantially improve the accuracy of these predictions, especially for high velocity impacts, but also to extend them to cases where the impact area is composed of ice or lunar-type regolith, as well as to cases where the asteroid is a porous "rubble pile." Furthermore, the cratering efficiency could be improved through the use of a small conventional explosive payload, an option that would likely require tradeoffs in the impactor design and mission architecture.

A practical concern of any kinetic-impact approach of mitigating the threat of asteroids is the risk that the impact could result in the fragmentation of the asteroid, which could substantially increase the damage upon Earth impact.[33] The energy required to fragment an asteroid depends critically upon the asteroid's composition and structure. For example, for a 200-m asteroid composed largely of ice, the disruption energy is approximately 3.4×10^{10} J. Since the kinetic energy of a 150-kg impactor at a relative velocity of 70 km/s would be 3.7×10^{11} J, the 200-m ice asteroid would likely fragment.[34] A 200-m asteroid composed largely of silicates would have a disruption energy of approximately 2.3×10^{12} J, about six times larger than the kinetic energy delivered by the interceptor; this asteroid would likely stay intact.[34]

Thus, the feasibility of the most kinetic-impact approaches for deflecting an incoming object depend on its size and composition (e.g., solid body, porous rubble pile, etc.), as well as the time available to change its orbit. An accurate determination of the composition of the target asteroid is a critical part of the kinetic-impact approaches, which may require a separate inspection mission. A further study is also needed to optimize impactor size, relative impact velocity, and the total number of impactors as functions of asteroid size and composition, to ensure a deflection attempt does not cause fragmentation.

B. Solar Sailing KEI Mission Description

The proposed solar sailing mission of mitigating the threat posed by NEAs is illustrated here using AIAA's asteroid mitigation problem described in Section III.

The proposed solar sailing mission is basically comprised of the initial cruise phase from 1 AU to a heliocentric orbit at 0.25 AU (1.5 years), the cranking orbit phase of a 168-deg inclination change (3.5 years), and the final retrograde-orbit phase (1 year) prior to impacting the asteroid at its perihelion. The proposed mission of intercepting, impacting, and deflecting NEAs is basically exploiting the unique, propellantless nature of a solar sail propulsion system capable of achieving a retrograde heliocentric orbit in order to increase the relative speed of a kinetic impactor. The solar sailing phase of the proposed mission architecture is similar to that of a rendezvous mission with Halley's comet, extensively studied by NASA/JPL in the mid-1970s.[15–18] Although the rendezvous mission with Halley's comet became an ill-fated mission concept requiring an 800-m solar sail for an 850-kg payload/bus, the mission concept demonstrated the unique capability of a solar sail for achieving a 145-deg orbital inclination change at 0.25 AU to rendezvous with Halley's comet for the 1986 passage. However, the mission proposed in this paper requires a moderate size, 160-m solar sail. Such a moderate-size solar sail is also being considered for the Solar Polar Imager (SPI) Vision mission to achieve a heliocentric mission orbit with an inclination of 75-deg at 0.48 AU from the sun. The solar sailing trajectory of achieving a 75-deg inclination at 0.48 AU is illustrated in Fig. 3 for the SPI Vision mission.[21] The mission of intercepting an asteroid will continue such an orbit cranking maneuver (but at 0.25 AU) to achieve a 168-deg inclination change. The final retrograde-orbit phase prior to impacting the asteroid at its perihelion (0.75 AU), is illustrated in Fig. 4.

Furthermore, the proposed mission concept will be significantly enhanced by NASA's Deep Impact mission,[35] which will explore the internal structure and composition of the nucleus of comet Tempel 1 before, during, and after impacts, and return the observations to Earth. The Deep Impact mission is not intended to deflect the orbit of such a large 6-km comet. The Deep Impact spacecraft was launched on January 12, 2005 and will release a 370-kg impactor spacecraft which will, on July 4, 2005, create a crater approximately 20-m deep and 100-m wide on the surface of the 6-km target comet, as illustrated in Fig. 5. The impact velocity will be 10 km/s, and the attitude/position of the impactor spacecraft after being released from the flyby spacecraft will be precisely controlled to achieve a 300-m targeting accuracy. The resulting impact ΔV will be practically zero, however.

The European Space Agency (ESA) has recently selected a small kinetic-energy impactor precursor

Mission Design
Solar Sail Trajectory Overview

Transfer Flight Path

- General Design Optimizes Thrust Vector Pointing
  - * Cruise trajectory produces 15° heliocentric inclination change
  - * Thrust vector change rates are minimized
  - * Solar-vector to Sail-Normal-vector angle is constrained to ≤ 45°
- 2-phase Approach Optimized for Insertion to OPS Orbit in ~6.8 years
  - * Cruise trajectory produces 15° heliocentric inclination change
  - Cranking orbit effects ~53° inclination

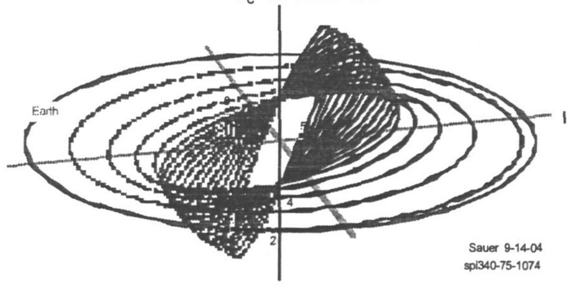
change

into the OPS orbit 60° heliocentric inclination
  - * Orbit trim is designed for final orbit shaping and velocity matching

Science OPS Orbit

- Designed for High Latitude Coverage with 3:1 Earth Resonance
  - * Nodal phasing included for control of Earth-Sun-S/C angle

2012 Solar Sail Solar Polar Imager
3:1 Resonance, R= 0.48 AU
75 Degrees Heliographic Inclination
a_c=.35 mm/s^2 CP1



	DATE	Δ Days	Δ Years	MET Days	MET Years
Launch C_3=0.25 km^2/s^2	05/24/12	0	0	0	0.000
Start of Sail Phase	06/03/12	10	0.027	10	0.027
Start of Cranking Phase	12/10/14	920	2.519	930	2.546
End of Cranking Phase	02/05/19	1518	4.156	2448	6.702
Start of Science OPS Phase	03/02/19	25	0.068	2473	6.771

Figure 3. Illustration of the Solar Polar Imager (SPI) Vision mission concept by NASA JPL.[21] This SPI mission, employing a 160-m solar sail, will provide significant technological advances required for the proposed solar sailing mission of mitigating the threat of NEAs.

mission (named the Don Quijote mission), as illustrated in Fig. 6, targeted for the 500-m asteroid (10302) 1989 ML.[14,36] The Don Quijote mission consists of two nearly identical spacecraft: A 400-kg orbiter (Sancho) and a 380-kg impactor (Hidalgo). The impactor spacecraft will utilize Earth and Venus flybys to achieve an impact velocity of at least 10 km/s. The resulting impact ΔV will be very small but measurable (probably, less than 0.01 cm/s). Its mission objective is to measure the actual translational/rotational momentum transfer of the impact, impact crater/ejecta, and surface/internal properties before/after impact.[14,36]

To mitigate the real threat of NEAs in the future, a separate inspection mission similar to Deep Impact and Don Quijote will be required as an integral part of any large-scale mission of deflecting NEAs. Real missions such as Deep Impact and Don Quijote will thus provide significant technological advances required for the proposed solar sailing kinetic impactor mission of mitigating the threat of NEAs.

The proposed solar sailing KEI mission will provide a relatively high impact velocity of at least 70 km/s, compared to a typical impact velocity of 10 km/s of conventional missions with the gravity-assist flyby maneuvers. However, the proposed mission will require at least ten KEI sailcraft. Each KEI sailcraft consists of a 160-m, 150-kg solar sail and a 150-kg microspacecraft impactor. A characteristic acceleration of at least 0.53 mm/s^2 is required to intercept the target asteroid in 5 to 6 years. The KEI sailcraft with a fully deployed solar sail first spirals inwards from 1 AU to a heliocentric orbit at 0.25 AU, followed by a cranking orbit phase for a 168-deg inclination change. After completing the cranking orbit phase, the KEI sailcraft then spirals outwards in a retrograde orbit to intercept the target asteroid 2004WR, as illustrated in Fig. 4. A total flight time of 6 years will be required prior to impacting 2004WR at its perihelion on January 1, 2012. Each impactor, with a relative impact velocity of at least 70 km/s, will cause a conservatively estimated ΔV of 0.3 cm/s in the trajectory of the 200-m target asteroid, due largely to the impulsive effect of material ejected from the newly-formed crater. The deflection caused by a single impactor will increase the Earth-miss-distance by $0.45R_\oplus$ where $R_\oplus$ denotes the Earth radius of 6,378 km. Therefore, at least ten KEI sailcraft will be required to increase the Earth-miss-distance by $4.5R_\oplus$. Because of a possible launch failure, physical modeling uncertainties, and mission reliability, we may have to launch more than ten KEI

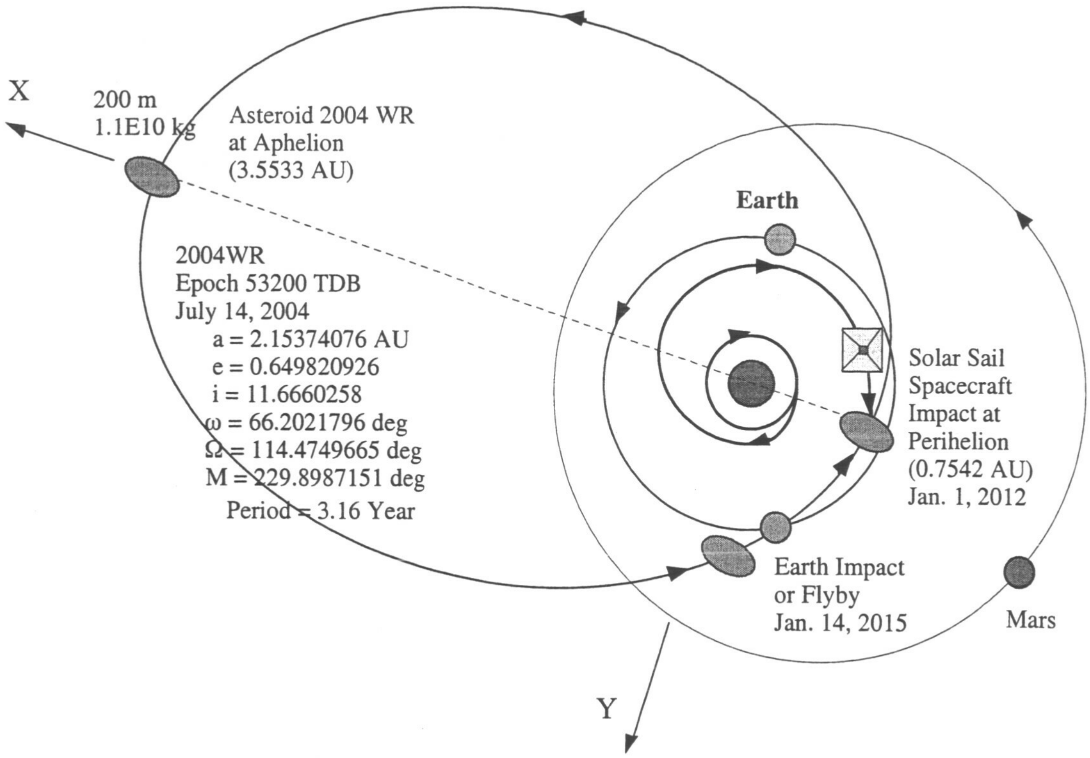


Figure 4. **Illustration of the solar sailing KEI mission for intercepting/impacting/deflecting a near-Earth asteroid. The final, retrograde heliocentric orbit phase (starting from 0.25 AU) results in a head-on collision with the target asteroid at its perihelion (0.75 AU).**

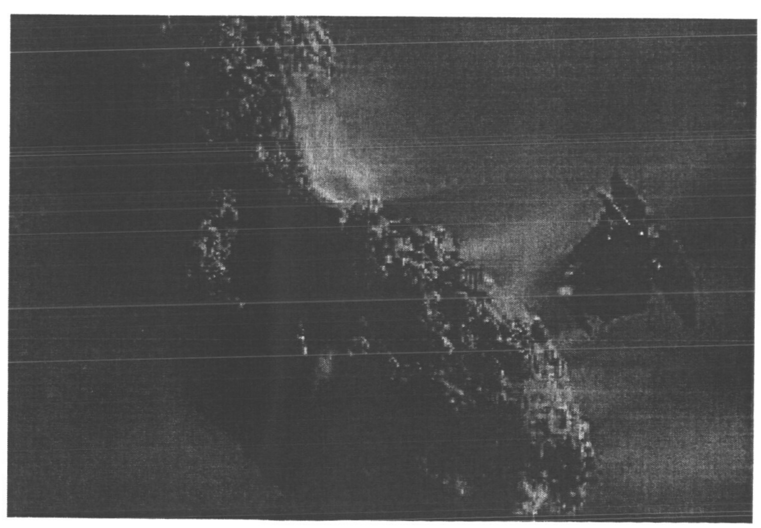
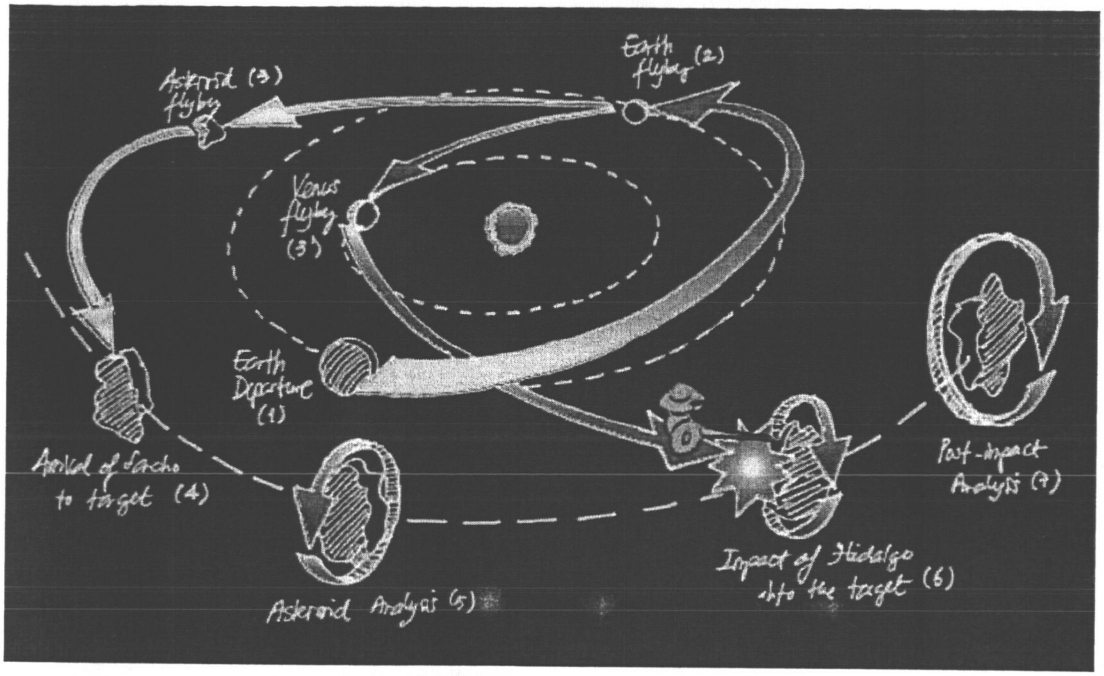


Figure 5. Illustration of the Deep Impact mission by NASA.[35] A 370-kg impactor spacecraft released from the flyby spacecraft is scheduled to impact with the 6-km target comet on July 4, 2005. The resulting impact ΔV will be extremely small and will not be measurable.



Don Quijote Baseline Trajectory Design

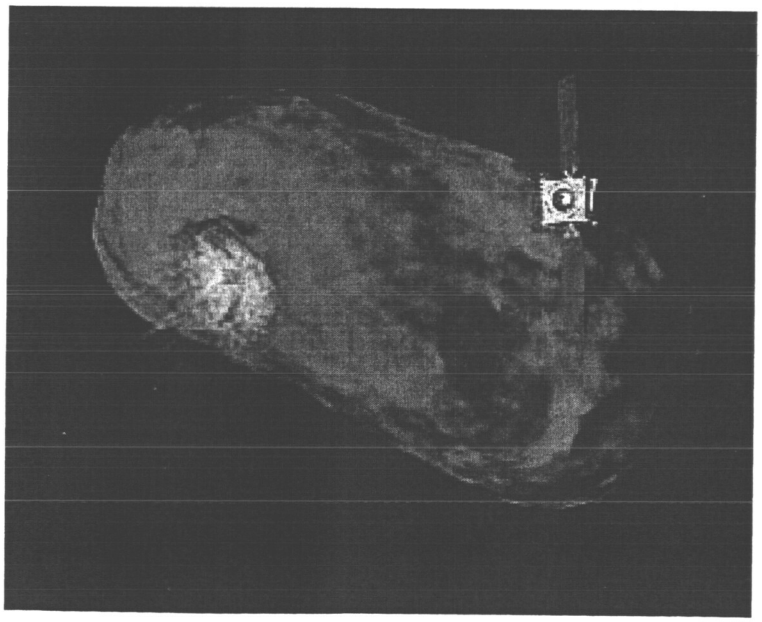


Figure 6. Illustration of a kinetic-energy impactor precursor mission by ESA, named the Don Quijote mission.[36] A 380-kg impactor spacecraft (Hidalgo) impacts with a 500-m asteroid while an orbiter (Sancho) observes the impact. The resulting impact ΔV will be very small (probably, less than 0.01 cm/s), but it will be measurable.

Table 1. Mass properties of scalable sailcraft of ATK Space Systems.[23,25,26]

Sail Size	40	80	160	240	320	m
Geometry						
Mast length	28	56	113	170	226	m
Mast diameter	0.4	0.4	0.6	0.6	0.6	m
Bending EI	82,441	82,441	438,847	438,847	438,847	N-m^2
Torsional GJ	197	197	453	453	453	N-m^2
Scallop factor	75	75	75	75	75	%
Sail area	1,200	4,800	19,200	43,200	76,800	m^2
Solar thrust (max)	0.01	0.04	0.16	0.36	0.64	N
cm/cp offset[a]	0.1	0.2	0.4	0.6	0.8	m
Mass						
Sails	6	19	67	100	200	kg
Masts	7	14	60	90	120	kg
Tip mass (each)	1	2	2	3	5	kg
Central assembly	8	10	15	20	30	kg
Sailcraft bus/impactor	100	125	150	400	500	kg
Total mass	125	176	300	622	870	kg
Characteristic acceleration[b]	0.08	0.23	0.53	0.58	0.73	mm/s^2
Inertia						
I_x (roll)	4,340	40,262	642,876	3.0E6	6E6	kg-m^2
I_y (pitch)	2,171	20,136	321,490	1.5E6	3E6	kg-m^2
I_z (yaw)	2,171	20,136	321,490	1.5E6	3E6	kg-m^2

[a]0.25% uncertainty of the overall sail size is assumed.
[b]the solar thrust divided by the total mass (at 1 AU).

sailcraft to mitigate the threat posed by a 200-m asteroid.

A conventional Delta II 2925 launch vehicle is capable of injecting at least two KEI sailcraft into an earth escaping orbit at $C_3 = 0.25$ km^2/s^2. Although the proposed mission concept requires a mission lead time of at least 10 years, it can be applicable to asteroids larger than 200 m by simply increasing the total number of 160-m, 300-kg sailcraft. Note that a Delta IV-Heavy (4250H-19) launch vehicle is capable of injecting a 9,300-kg payload into an earth escaping orbit at $C_3 = 0$ km^2/s^2.

A variety of technical issues inherent to the proposed concept must be further examined to make the proposed concept to become a viable option of the Earth protection system. Tradeoffs are required to design a baseline mission architecture by considering technology readiness levels, cost, system complexity, feasibility, reliability, etc. For example, mass properties of solar sails of various sizes are provided in Table 1. A 240-m solar sail can deliver a 400-kg impactor spacecraft in 5 years to a larger target asteroid; however, it will be more difficult to deploy and control such a 240-m solar sail, and thus system-level tradeoffs are needed to optimize the overall mission architecture. Furthermore, for larger asteroids, the impactor spacecraft may not have to be separated from the solar sail; the complete solar sail spacecraft could be designed to impact with a larger asteroid and increase the resulting ΔV. The differing sizes and compositions of asteroids could require a family of impactors, some containing small conventional explosive payloads to increase cratering efficiency. Concerns as to fragmentation may require the use of smaller impactors, or even different orbits that allow deflection at lower relative velocities.

The critical, enabling technologies required for the proposed mission include: Deployment and control of a 160-m solar sail, development of microspacecraft bus able to withstand the space environment only 0.25 AU from the sun, precision solar sailing navigation, terminal guidance and targeting (accuracy better than 100 m at an impactor speed of 70 km/s), and impact-crater ejecta modeling and accurate ΔV prediction. A 160-m solar sail is not currently available, and the deployment and control of such a large solar sail in space will not be a trivial task. However, a variety of near-term solar sailing missions requiring 160-m solar sails and the associated solar sail technologies are being developed.[20–27] In particular, a 160-m solar sail will be required for the SPI Vision mission, which is one of the Sun-Earth Connections solar sail roadmap missions currently envisioned by NASA.[21,22] Furthermore, the Deep Impact mission by NASA, with a scheduled impact with a comet on July 4, 2005, will also provide significant technological advances required for the proposed solar sailing mission of mitigating the threat of NEAs.

C. Solar Sailing Flight Phase Simulation

The proposed solar sailing mission is basically comprised of the initial cruise phase to 0.25 AU (1.5 years), the cranking orbit phase of a 168-deg inclination change (3.5 years), and the final retrograde orbit phase (1 year) prior to impacting the asteroid at its perihelion. Preliminary simulation results showing these three distinct flight phases are provided in Figs. 7 through 9. The exact launch date of this proposed mission for the AIAA asteroid problem has not been determined yet. A simple in-plane steering law, employing a fixed 35-deg tilt angle, was used for both the initial cruise phase of spiraling inwards and the final retrograde phase of spiraling outwards. The spiral trajectories shown in Figs. 7 and 9 are not the so-called logarithmic spiral trajectories because their initial flight path angles are zero, not the required spiral angles. An out-of-plane steering law of $\pm$35-deg tilt angle change every half orbit was employed for the cranking orbit phase. More detailed study results for optimal trajectory design and thrust vector control design can be found in Refs. 37 and 38.

D. Technology and Mission Development Plan

Several critical space missions, which will be making significant technological advances for the development of Solar Sailing KEI Vision/Demo Mission, are:

- Deep Impact mission by NASA (a scheduled impact with a comet on July 4, 2005)
- Don Quijote mission by ESA, 2015 (?)
- New Millennium Program ST9 flight validation mission of a 40-m Solar Sail, 2015 (?)
- Solar Polar Imager (SPI) mission with a 160-m solar sail, 2025 (?)
- Solar Sailing KEI flight validation mission, 2030 (?)

V. Conclusion

This paper has presented a realistic near-term solution to mitigating the threat posed by incoming hazardous asteroids. The solar sailing phase of the proposed mission architecture is comprised of the initial cruise phase to 0.25 AU, the cranking orbit phase, and the final retrograde orbit phase prior to impacting the target asteroid at its perihelion. A head-on collision causes an impact velocity of at least 70 km/s, which is much higher than a typical impact velocity of 10 km/s of conventional missions such as NASA's Deep Impact mission and ESA's Don Quijote mission. The proposed mission will require at least ten KEI sailcraft to increase the Earth miss distance by at least $4.5R_\oplus$ for a 200-m target asteroid. For larger asteroids, the impactor spacecraft may not have to be separated from the solar sail; the complete solar sail spacecraft could be designed to impact with a larger asteroid and increase the resulting ΔV. The critical technologies required for the proposed mission include: Deployment and control of a 160-m solar sail, development of microspacecraft bus able to withstand the space environment only 0.25 AU from the sun, precision autonomous solar sailing navigation, terminal guidance and targeting (accuracy better than 100 m at an impactor speed of 70 km/s), and impact-crater ejecta modeling and accurate ΔV prediction. A 160-m solar sail is not currently available. However, a 40-m solar sail is being developed by NASA and industries for a possible flight validation experiment within 10 years, and a 160-m solar sail is thus expected to be available within 20 years.

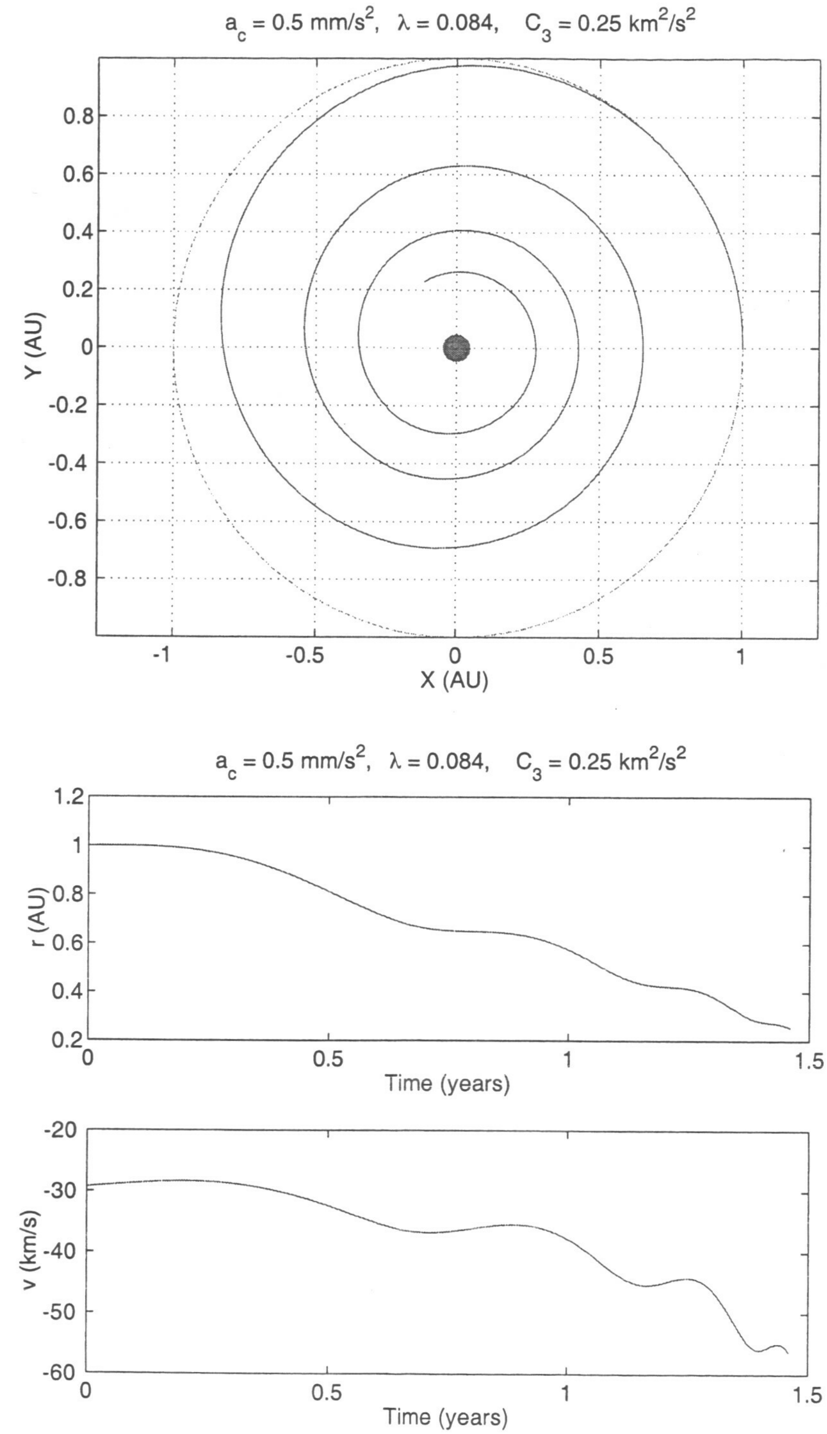


Figure 7. The initial cruise phase in a prograde heliocentric orbit from 1 AU to 0.25 AU. The actual launch date needs to be appropriately selected to intercept the target asteroid at its perihelion on January 1, 2012.

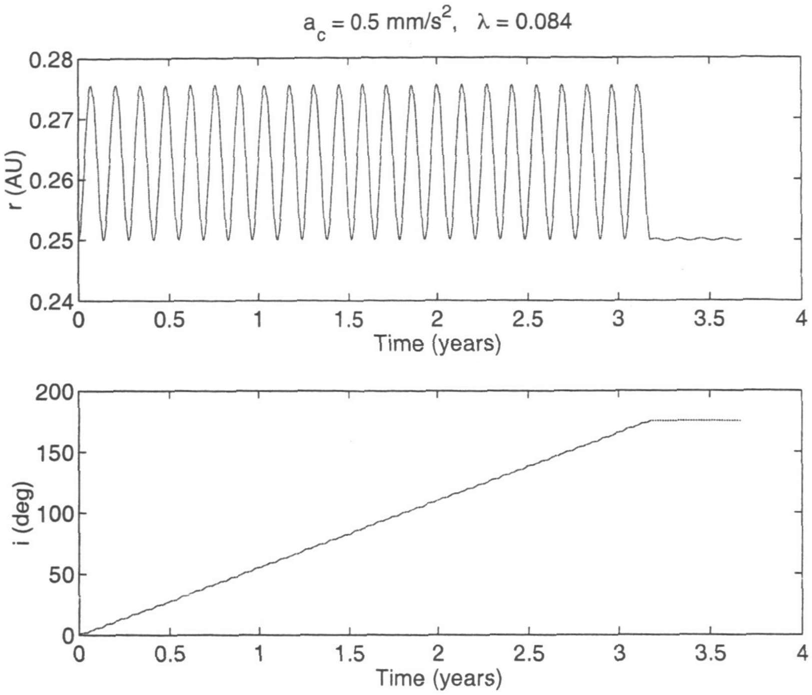


Figure 8. Time histories of orbital radius and inclination during the cranking orbit phase of reversing the flight direction from a prograde orbit to a retrograde orbit.

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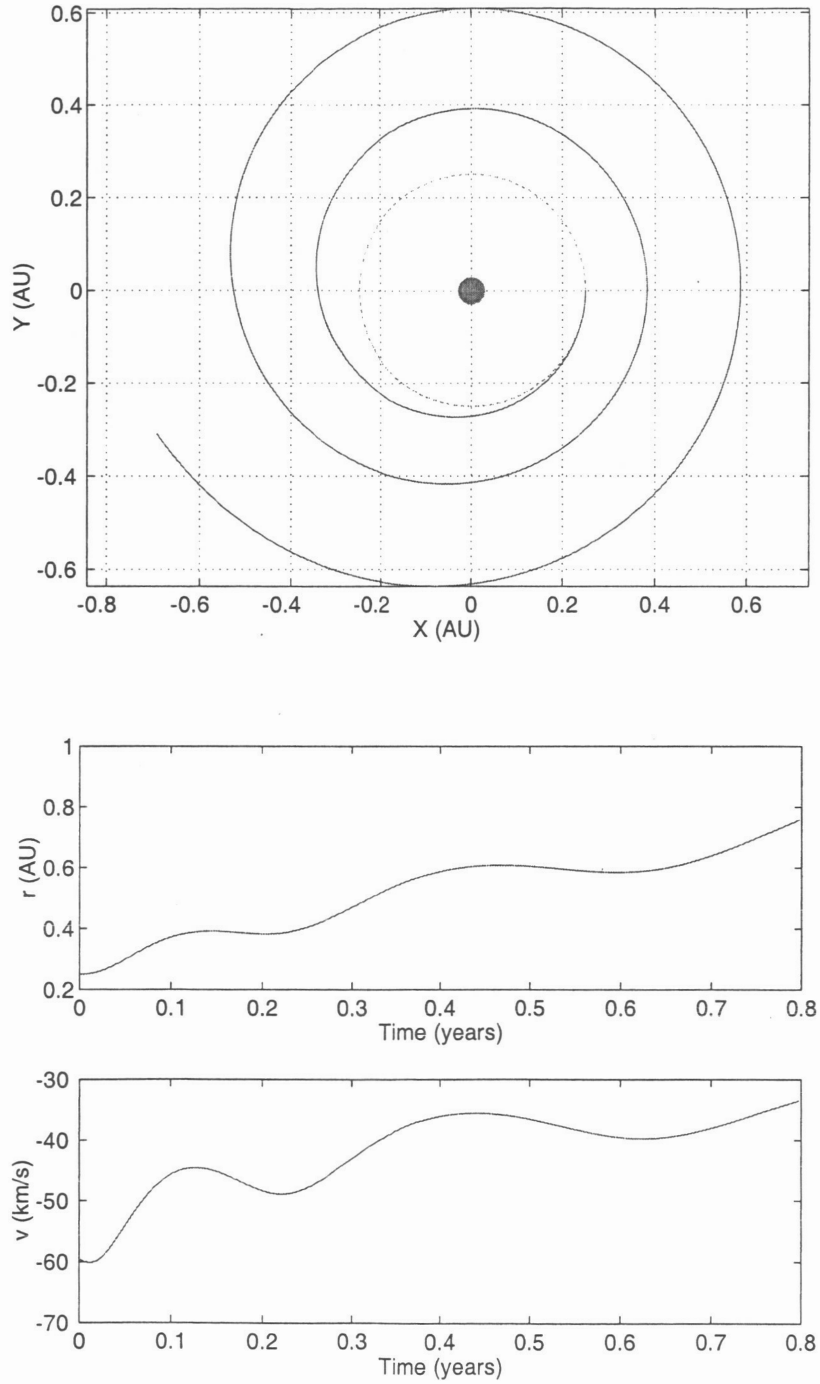

Figure 9. The final, retrograde heliocentric orbit phase (starting from 0.25 AU), which results in a head-on collision with the target asteroid at its perihelion (0.75 AU).

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